

# Life cycle assessment of integrated circuit packaging technologies

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## Abstract

**Background, aim and scope** Nanostructured polymer particles are produced to be used in ball grid array (BGA) and chip scale packaging (CSP). The technology could replace conventional BGA and CSP metal balls, and the hypothesis is that the shift could be eco-efficient as polymer core particles increase the reliability. For the first time, these particles are environmentally evaluated. **Materials and methods** The change in GWP100 and Eco-Indicator'99 (H) scores when replacing traditional component packaging, here quad flat pack to BGA/CSP, was explored both on component and printed circuit board assembly (PCBA) level. This was followed by comparisons between BGA packages using different types of metal-plated mono-dispersed polymer particle (MPP) balls and conventional balls, respectively.

**Results and discussion** For BGAs, the silicon (Si) die dominates CO<sub>2</sub>e emissions, but for Eco-Indicator'99(H), solder balls are not negligible. Excluding the Si die and component assembly, the LFBGA-84 to WCSP-64 would reduce CO<sub>2</sub>e by about 98% and Eco-Indicator'99 (H) by about 90%. Overall, for BGA–256 using same size balls, gold-plated MPP technology decreases the Eco-Indicator'99 (H) score by about 25% compared to Pb-based or Pb-free

balls. Gold production dominated GWP100 and Eco-Indicator'99 (H) for the gold-plated MPP. Each microsystem is unique, and new environmental impact estimations must be done for the sub-structures of each electronic device. Screening process-sum life cycle assessment (LCA) gives similar understanding of impacts as resource productivity methods. Even though the metal mass per ball is greatly reduced, it is a weak indicator of environmental impacts which are driven by each material's specific environmental characteristics.

**Conclusions** The ball share of the BGA-256 GWP100 and Eco-Indicator'99 (H) score is small, and the BGA/CSP producers can marginally improve the environmental performance by focusing on the balls. On a comparable IC packaging basis, the introduction of WCSP packaging technology implies a significant environmental footprint reduction. On PCBA level, the contribution of BGA balls is negligible. Results for metal-plated MPP BGA balls suggest that gold usage is the key environmental performance indicator of interest.

**Recommendations and perspectives** Even though WCSP clearly reduces the component level impacts, the PCBA (board) level impact could increase as the CSP miniaturisation is paralleled with more PWB layers. This effect should be included in further system expansions. For LCA, in general, update of all LCIA methods, which include ozone depletion, with the latest results for dinitrogen monoxide is needed.

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**Keywords** Ball grid array · Chip scale package · Electronic device · Integrated circuit · Monodispersed polymer particle · Printed circuit board assembly · Screening LCA

## 1 Background, aim and scope

It is well-known that exploration of environmental issues is preferably treated within a multidisciplinary system–analytical problem frame. Life cycle assessment (LCA) has the potential to point out important costs and benefits from an environmental point of view. LCA year after year shows its usefulness in separating rather small and distinct product systems or technologies, recently, e.g. for polyols (Helling and Russell 2009) and toys (Muñoz et al. 2009). The latest decades, the electronics industry has undergone tremendous changes due to intense research leading to advanced technology development. However, only a few studies (Liu et al. 1999; Nissen 2001) have been published on environmental implications of different micro/nano-systems packaging technologies providing same benefit. A possible reason is the large amounts of data required by the LCA tool of complex electronic products using many technologies. For micro/nanoelectronics packaging, it could be more worthwhile quantifying smaller systems, however having the larger perspective in mind. Packaging technology is here divided into six levels: (1) the wafer, (2) the integrated circuit (IC), (3) the multichip module, (4) the printed board assembly, (5) the motherboard and (6) the system (e.g. a laptop; Andersson 2007). Referring to levels 2–4, nanostructured polymer particles are produced especially for usage within anisotropic conductive adhesive (ACA) used at level 2 and 4. Interconnection materials are strongly connected to this research as they are almost identical to solder balls, in turn possible to replace with metal-plated polymer balls (Andrae 2009).

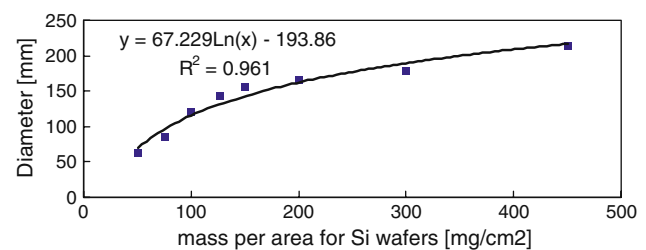
ACAs are one of three major groups of electrically conductive adhesives which also encompasses isotropic and non-conductive. ACA pastes usually consist of diglycidyl ether of bisphenol F or diglycidyl ether of bisphenol A as polymer matrix, imidazoles as curing agents, and different types of Ag powders or Au-coated polymer spheres as conductive particles. ACA technology is capable of finer pitch interconnect which can reduce Si die and component size. Traditionally, ACA has been used to attach chips to package leadframes and chips directly to the printed wiring board, so-called flip chip technology (Cao et al. 2005). Furthermore, metal-plated monodispersed polymer particles (MPP) can be customised for applications such as ball grid array (BGA) and chip scale packaging (CSP). BGA is a surface-mount package that utilises an array of metal spheres or balls as means of providing external electrical interconnection, as opposed to the pin-grid array (PGA) which uses an array of leads for that purpose. The balls are composed of solder, and are attached to a laminated substrate at the bottom side of the package. The Si die of the BGA is connected to the substrate either by wire-

bonding or flip chip connection. At level 2, metal-plated MPP ball technology could replace conventional metal balls for BGA and CSP applications, and the hypothesis is that the shift will be eco-efficient for several reasons: the polymer core particles increase the reliability by improving the interconnection compliance compared to compact metal cores (He et al. 2007), and smaller-sized metal-plated MPP balls can achieve even higher reliability in BGA/CSP (He et al. 2008). The smaller the particle size is, the stiffer the particle behaves. Moreover, it has been predicted that by introducing polymer cores, the heavy metal use, for the same size balls, can be reduced by a factor of 3–7 (Whalley and Kristiansen 2008). For the first time, the present paper will broadly explore the possible life cycle eco-efficiency of polymer core solder balls (from their product system perspective) and propose guidelines for evaluation of similar systems.

## 2 Materials and methods

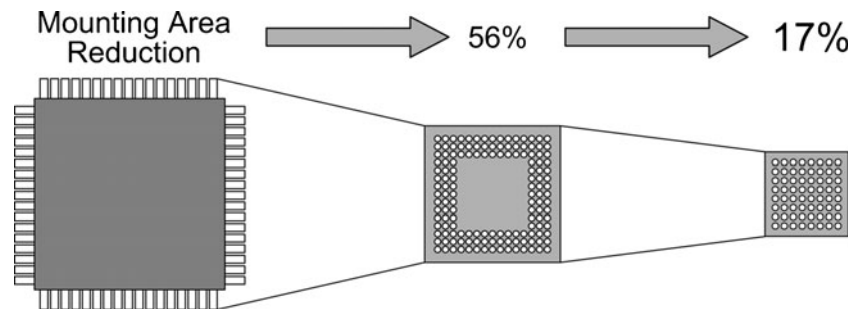
The cradle-to-gate carbon footprint varies considerably for different silicon wafers. The deciding parameters are roughly yield, number of Si die per wafer, and wafer volume. A recent Taiwanese study reports 146 kg CO<sub>2</sub> per 8-in. memory wafer having 1,100 gross Si die, i.e. 0.13 kg/Si die (Liu et al. 2010). Boyd et al. reported 6 kg CO<sub>2</sub>/Si die for a 300-mm 0.775-mm-thick 45-nm node CMOS wafer with 590 gross silicon die (Boyd et al. 2009). Compared to Boyd et al. (2009), Liu et al. (1999) excluded silicon wafer production and infrastructure. Per mass of Si die, the carbon footprints are 9,800 and 30,300 kg CO<sub>2</sub>/kg for Liu et al. (1999) and Boyd et al. (2009), respectively.

A hypothesis previously used for IC final assembly electricity usage is a 25% addition to the wafer fabrication electricity usage (European Commission 2005). Probably, other proxies are also relevant, e.g. “per connection to the Si die” or “per Si area processed in the back-end processes”. In this research, an approach was adopted which combines the much WWW-presented



**Fig. 1** Possible correlation between the diameter and mass per area of Si wafers

**Fig. 2** Graphic of miniaturisation on package level from TQFP to LFBGA to WCSP



silicon die masses of specific ICs, the proxy 0.34 kWh electricity/cm<sup>2</sup> in final assembly (Microelectronics and Computer Technology Corporation 1993) and the median proxy 150 mg Si/cm<sup>2</sup> as shown in Fig. 1. For the back-end final assembly of microchips, Nissen mentioned 110 kWh electricity/kg (Nissen 2001, p. 90), and the present approach has similar order of magnitude.

Ecoinvent's "Electricity, production mix CN/CN U" was used to model the electricity production in this study.

### 2.1 Relative share of different parts of ball grid array microcircuits

The relative environmental impact share of BGA balls compared to other parts of a BGA package was estimated by calculating screening cradle-to-gate LCA scores for a metal BGA (Xilinx 2007) using balls made of 63 Sn–37 Pb and 95.5 Sn–3.9 Ag–0.9 Cu alloy. In a material content declaration from 2007, the *Si die attach* part (75 wt.% Ag) was 0.23 wt.% and *solder balls* (made of 63 Sn–37 Pb) were 16 wt.% of the total weight 11 g. No primary data for manufacturing of sub-parts were collected for the comparison between Pb and Pb-free BGA-560 packages.

Manufacturing of metal solder balls is described in Section 2.4.

One kilowatt hour ( $\pm 0.1$  kWh) electricity/kg was assumed for relatively simple (intermediate) processes such as "Heat spreader production". Nevertheless, solder ball and metal-plated MPP ball production is described in Section 2.4. It is likely that raw material production is more important than material processing for the sub-parts (except the Si die) of present IC component. The GWP100 and Eco-Indicator'99 results are shown in Fig. 6.

### 2.2 Consequence of miniaturisation from TQFP to LFBGA to WCSP

It is commonly assumed that the miniaturisation of packaging concepts will lead to environmental benefits. Component packaging concepts can only be compared if an identical Si die is "stored" inside the package. Microchips are comparable if they can contain the same Si die size (Nissen 2001). The Si die size determines how many input–output connections are possible and those cannot be proportionally different if the comparison shall be valid. Here follows a microcontroller example from OKI Semiconductor of "older" and "newer" packaging concepts. The example concerns reported material content declarations for Thin Quad Flat Pack 64 (TQFP–64; OKI 2009a), low-profile fine-pitch ball grid array (LFBGA–84; OKI 2009b), and Wafer CSP-64 (WCSP–64; OKI 2009c; equal Si die mass of 16.9 mg). Figure 2 shows a graphic of the mounting area reduction. But what is the potential environmental gain of such a component miniaturisation? For this comparison, the Si die has the same mass for the old and new concept, but the amount and composition of additional packaging materials differ.

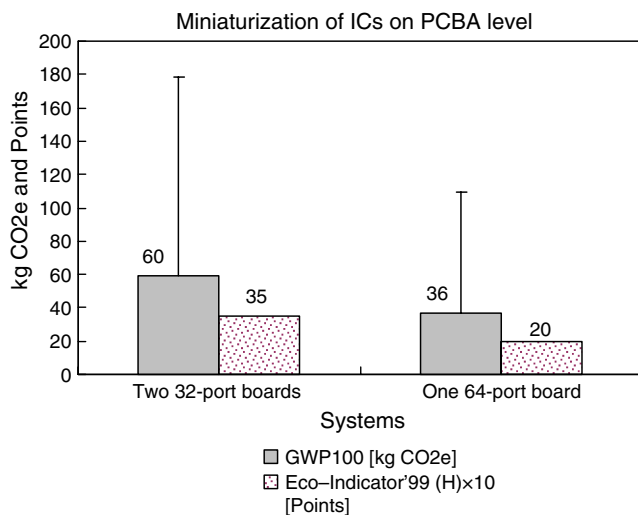
Examples of GWP100 and Eco-Indicator'99 results for these package types are shown in Figs. 7 and 8.

### 2.3 Consequence of miniaturisation for the environmental impact of printed board assemblies

According to Toshiba, The PCBA footprint could be reduced for a specific product by around 50% by resource saving design (Toshiba 2010). Here follows another example in which the IC miniaturisation effect is explored

**Table 1** Inputs for ADSL PCBA miniaturisation calculation

	ICs [#]	Mass ICs ~[g]	Si dies, mass ~[g]	Si dies, area ~[cm <sup>2</sup> ]	Gold, ~[g]	I/Os [#]
Two 32-port PCBAs	96	93	1.6	8.7	0.3	9,268
One 64-port PCBA	56	56	0.98	5.5	0.14	5,812



**Fig. 3** The estimated effect of IC miniaturisation on environmental impacts on ADSL board level

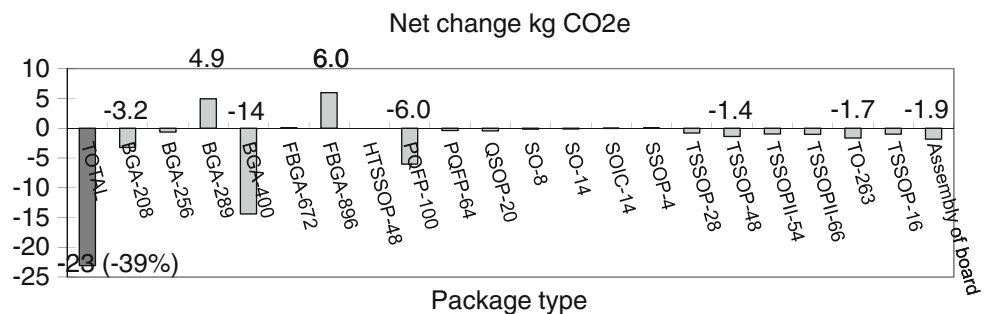
for an ADSL product (Confidential source 2010). Between product generations, two 32-port PCBAs could be integrated to one 64-port PCBA; whereby several QFPs were naturally replaced by BGAs, components were omitted and integrated to higher density BGAs. Table 1 shows the key data and Fig. 3 the CO<sub>2</sub>e achievement as far as ICs.

Although two PCBAs were replaced by one, the above indicators were not reduced by 50%, and subsequently were not the carbon footprint (40% reduction) and Eco-Indicator'99 (43% reduction) linearly reduced according to number of PCBAs. The explanation is to be found on IC component level.

Even though the absolute uncertainty is relatively high (see Fig. 3), Monte Carlo simulations in SimaPro 7.2.3 showed that the probability is 100% (for all GWP100 gases thanks to *process correlation*) and that the miniaturisation is beneficial. The uncertainty of GWP100 indices would cancel each other and would not change the probability much. Figure 4 shows the package type contributions for GWP100.

Note that the carbon footprint is only for ICs and no other electronic components.

**Fig. 4** Net change in CO<sub>2</sub>e for different IC package types on ADSL board level



## 2.4 Consequence of different BGA ball materials: BGA-256 example

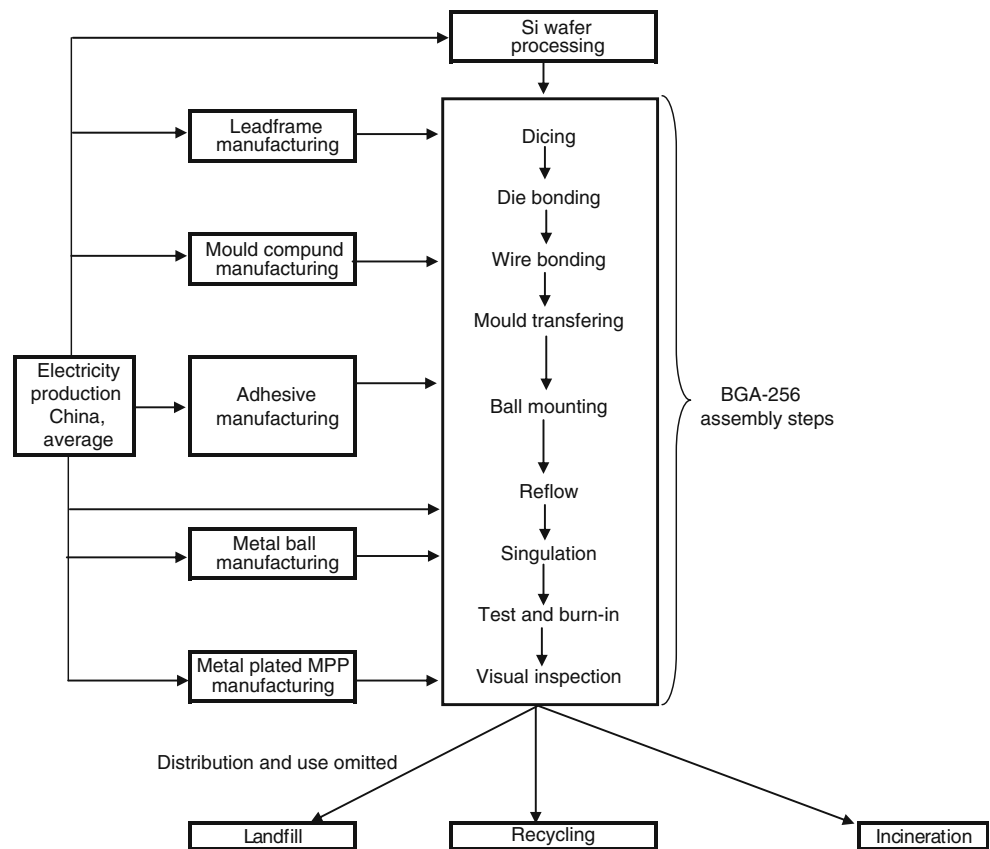
Here follows a section where BGA-256 by NXP® (package code SOT1018-1 and ball diameter 500 μm, NXP (Semiconductor 2010)) is explored for different types of ball materials. Five major parts constitute the BGA-256: adhesive (0.029 wt.%), mould compound (31 wt.%), Si die (2.5 wt.%), leadframe (53 wt.%), and the (Pb-free) balls (13 wt.%). All manufacturing including MPP are assumed to take place in China. These metal-plated MPP will only constitute 3.8–5.8 wt.% of the BGA-256 and lower its weight by 11%, but how eco-efficient is this advantage? The scope is shown in Fig. 5.

The conventional balls (metal ball production China) are produced by the *uniform droplet spray process* in which metals are melted and forced through an orifice, creating a laminar jet which is broken into uniform droplets (balls; Williams 1996, Yu et al. 2008). In Yu et al. (2008), for each experiment, about 200 g of solder alloy was filled into the crucible for spraying. Every experiment started with evacuating the chamber to 10 Pa and backfilling with pure nitrogen three times. The chamber pressure was maintained at 70 kPa after which the crucible was heated to 300°C, holding this temperature for 15 min. Anyway, the latest information is that the procedure uses a few kW and takes less than an hour (Chun 2009, personal communication). The assumptions are summarised in Tables 2 and 3.

MPP are produced (metal-plated MPP manufacturing) by first preparing the polymeric microspheres via the *Ugelstad process*, and then metallisation of the polymeric spheres. Per MPP, these emulsion polymerisation processes are very energy efficient compared to the uniform droplet spray process. But on the other hand, the plating processes seem to make the energy advantage uncertain.

The differences between “One BGA package using metal plated MPP” and “One current BGA package using conventional metal balls” are for starters the weight of the balls and the materials of which they are made. Also, ancillary chemicals and transportation differ; however, these two differences are omitted here due to lack of data.

**Fig. 5** The scope of the BGA-256 screening LCA



The volume of the metal-plated MPP is assumed identical to the Pb-based and Pb-free solder balls. For this research, four ball types, used in the same BGA, are reported.

The electricity usage for the Ugelstad process is composed of the amount needed to heat water and keep it warm for a few hours.

The electricity usage for plating processes per kilogram is calculated by the number of plated layers (3), MPP area including platings ( $7.9 \times 10^{-3} \text{ cm}^2$ ), electricity usage per area ( $2.7 \times 10^{-4} \text{ kWh/cm}^2$ , Ecoinvent 2009, Electroplating Nickel I) and metal-plated MPP mass ( $6.9 \times 10^{-8} \text{ kg}$ ).

#### 2.4.1 Calculation of the mass of one ball for MPP balls

The mass of one “Acrylate Cu SnPb” ball is 0.22 mg. The “Acrylate Cu AuNi” ball weighs 0.14 mg. Table 4 below shows the input values for arriving at these

weights. The density of polyacrylate is approximately  $1.2 \text{ g/cm}^3$ .

Pb-based (63 Sn–Pb 37) and Pb-free balls (96.5 Sn–3 Ag–0.5 Cu) weigh 0.62 and 0.54 mg, respectively, as 256 Pb-free balls weigh 140 mg and the densities of 63 Sn–Pb 37 and 96.5 Sn–3 Ag–0.5 Cu alloys are around 8.4 and  $7.3 \text{ g/cm}^3$ , respectively.

Transports, losses and ancillary materials are left out in this study due to knowledge gaps.

### 3 Results

#### 3.1 The GWP100 and Eco-Indicator’99 (H) shares of BGA-560 constituents

From Fig. 6, the preliminary conclusion can be drawn that solder balls are of small carbon significance for metal

**Table 2** Assumptions for manufacturing of metal solder balls

	Unit	Amount	2σ NORM
Output			
Production of metal solder balls	g	200	
Inputs			
Electricity	kWh	2.7	0.27

**Table 3** Assumptions for manufacturing of metal-coated polymer balls

	Unit	Amount	2σ NORM
Output			
Production of metal-plated MPP	g	1,000	
Inputs			
Ugelstad process, electricity	kWh	11	1.1
Plating processes, electricity	kWh	94	9.4

BGA-560 microchip packages and that the shift to Pb-free ball material does not necessarily lead to an environmental improvement.

In statistics, for a 90% confidence interval, according to the *standard normal curve*, there is a 90% certainty level that the true mean lies within certain bounds. According to  $\bar{x} = \pm 1.65 \times \frac{\sigma}{\sqrt{n}}$ , for a BGA-560 with Pb-based balls, for one ( $n=1$ ) Monte Carlo simulation (500 runs), the mean random sample ( $\bar{x}$ ) was 11.6 kg, total standard deviation ( $\sigma$ ) 4.9 kg, and 90% confidence interval 3.5–20. Actually, more than 30 Monte Carlo simulations ( $n>30$ ) are needed to build a useful confidence interval around the simulation results. Moreover, for GWP100, in 52% of the Monte Carlo runs, Pb-free BGA-560 was worse than Pb-based BGA-560, i.e. no difference.

The Si die production model from Boyd et al. (2009) was used for Section 3.1. The electricity for BGA-560 assembly was calculated as follows: Si die mass, 320 [mg]  $\times$  0.34 [kWh/cm<sup>2</sup>]:150 [mg/cm<sup>2</sup>]=0.7 kWh. This calculation originates from an algorithm for ICs which expresses the (global average) carbon footprint for any IC:  $m_{\text{die}}$  [mg]  $\times$  0.0308 [kgCO<sub>2</sub>e/mg] +  $m_{\text{die}}$  [mg]  $\times$  0.34/150 [kWh/mg]  $\times$  0.6 [kgCO<sub>2</sub>e/kWh] (Andrae and Andersen 2010).

### 3.2 Miniaturisation effect

Figures 7 and 8 show the GWP100 and Eco-Indicator'99 (H) effects of miniaturisation from TQFP-64 to LFBGA-84 to WCSP-64 by OKI Semiconductor.

Figure 7 gives a mixed message, and more investigations are needed to separate TQFP-64 and LFBGA-84. The effect on GWP100 and Eco-Indicator'99 (H) of changing 1,000 LFBGA-84 to the same number of WCSP-64 is shown below in Fig. 8.

Clearly, it would be very advantageous, seen from component packaging material viewpoint, to change to WCSP technology. The reduction from LFBGA-84 to WCSP-64 is 98% for GWP100 and 93% for Eco-Indicator'99(H), respectively.

### 3.3 The solder ball vs. metal-coated polymeric ball life cycle comparison

Figure 9 shows screening LCA results for BGA-256 microchips using different types of ball materials. Si die production and microchip assembly are excluded as they are assumed equal between the packages.

For GWP100, the Acrylate Cu AuNi MPP were worse than the Acrylate Cu SnPb MPP in 95% of Monte Carlo runs. Figure 10 shows the relative importance of processes for Acrylate Cu AuNi MPP.

## 4 Discussion

The electronics package can be resembled to a storage box in which the same Si die is stored. Consequently, there is a myriad of different ways in which the “storage box” can be designed: DIP, SOP, TSOP, QFP, BGA, CSP, flip chip, etc.

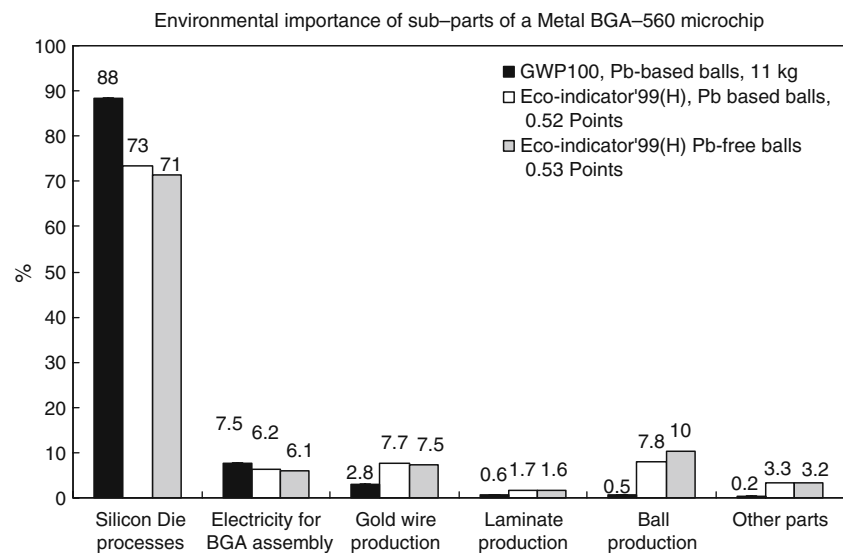
The ecoinvent database present *two* models of IC manufacturing from cradle-to-gate: one for memory type and one for logic type where the CO<sub>2</sub>e results are 500 and 1,000 kg CO<sub>2</sub>e/kg, respectively. This indicates that the benchmark intensity GWP100 results, for BGA-560 (1,174), BGA-256 (972 to 1,103), TQFP-64 (2,577), LFBGA-84 (3,345) and WCSP-64 (20,932), are fairly reasonable.

Nevertheless, it can be argued how ecodesign of BGA circuits can be done. One approach is to exclude the Si die

**Table 4** Basis for weight calculation of balls of total diameter 0.05 cm (500 μm)

Ball type	Radius polymer (cm)	Thickness (cm) copper layer	Thickness (cm) 63 Sn–Pb 37 layer	Thickness (cm) gold layer	Thickness (cm) nickel layer
Acrylate Cu SnPb	$2.4 \times 10^{-2}$	$1.0 \times 10^{-3}$	$2.0 \times 10^{-3}$	n.a.	n.a.
Acrylate Cu AuNi	$2.4 \times 10^{-2}$	$1.0 \times 10^{-3}$	n.a.	$1.0 \times 10^{-5}$	$1.0 \times 10^{-5}$

**Fig. 6** Environmental importance of sub-parts of a Metal BGA-560 microchip



and put the focus on the other parts, and at the same time evaluate the package using other impact categories than GWP100, as well as single indicators.

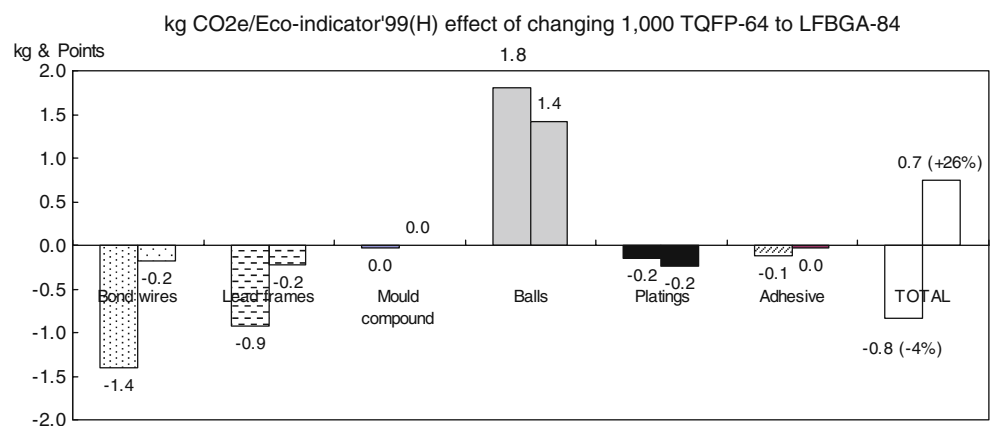
As shown in Fig. 6, the share of CO<sub>2</sub>e impacts in (GWP100) of solder balls is very small compared to other parts of the BGA. It does not matter if Pb-free or Pb-based balls are used; the Si die is the dominating part.

However, it is not certain what the experimental details found about the *uniform droplet process* means for industrial production of solder balls. Both electricity and nitrogen gas are used which could be significant per ball, but not likely per BGA. For the ball fabrication process, the emulsion polymerisation followed by metal plating is probably much less energy demanding. Over usage of gold, which is wasted, is not significant either. The gold used in leadframes is much more important than the gold used in BGA/CSP balls. However, as shown in Fig. 10, the ball plating process is a potential driver of impacts.

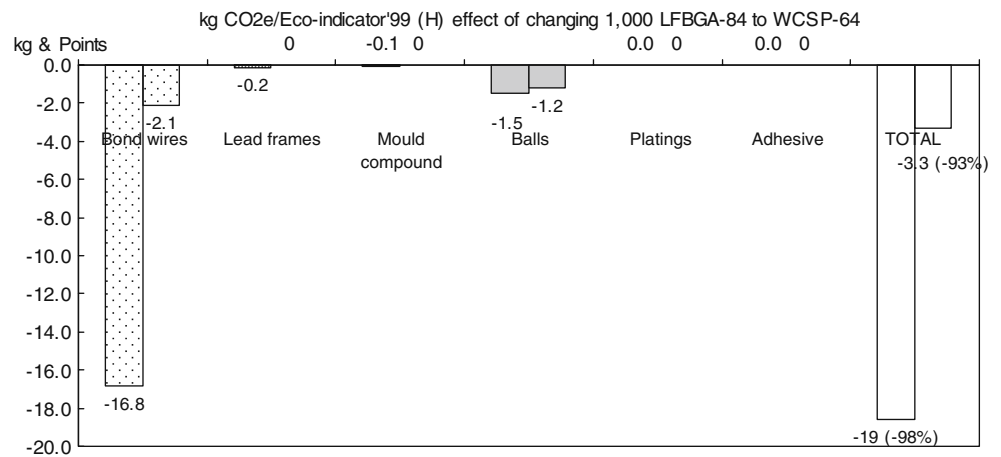
The solder balls, Pb or Pb-free, are a very small fraction (~1%) of the cradle-to-gate CO<sub>2</sub>e impact for a metal-based BGA of 560 balls. However, there exist several types of BGA packages: metal-based, plastic-based, low-profile fine-pitch, etc. The weight share of the solder balls fluctuates depending on BGA package type. Philips Semiconductors reported for *plastic* and *low-profile fine-pitch* BGAs. For those, the share of the solder balls was 0.020 and 11 wt.%, respectively. For BGA-256 (NXP Semiconductor 2010), the balls and Si die shares were 13 and 2.5 wt.%, respectively.

Figure 11 shows the result of resource productivity (RP) analysis for a specific PCBA (Alcatel-Lucent 2008). RP is defined as “annual unit production” divided by the “combined aggregated and dimensionless environmental impact between 0 and 1” (Luo et al. 2001). As, e.g., ICs and printed circuit boards have a high environmental impact compared to annual usage, they get a lower RP than, e.g., Sn for specific PCBAs.

**Fig. 7** The effect on GWP100 and Eco-Indicator'99 (H) of changing 1,000 TQFP-64 to 1,000 LFBGA-84



**Fig. 8** The effect on GWP100 and Eco-Indicator'99(H) of changing 1,000 LFBGA-84 to 1,000 WCSP-64



Alcatel-Lucent's RP approach does not necessarily give different conclusions for PCBA designers than plain process-sum LCA. Most PCBA LCAs also show that the PCB and the ICs have a similar relation (Joyce et al. 2010) as in Fig. 11.

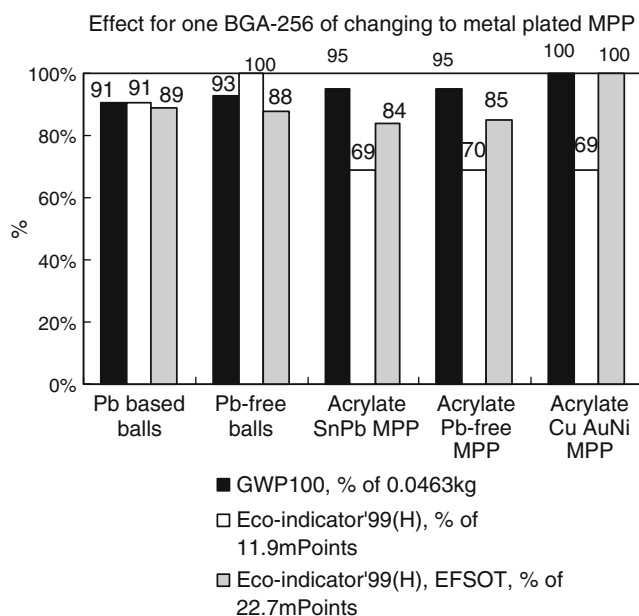
Using EFSOT's (PRE Consultants 2005) updated version of Eco-Indicator'99(H) which includes, e.g. gold and silver resource indices, did not change any conclusions in between BGAs shown in Fig. 9. This EFSOT version of Eco-Indicator also includes an impact category called "Human Toxicity" for which indices have been derived for several metal emissions to air, soil and water, including gold, silver, Pb and tin. Here, gold emissions (mainly from leadframes) could possibly be a concern counting with maximum possible emissions to water. That is, emissions

from polymer balls are of no concern as far as the current knowledge situation as 81 wt.% of the gold used in the BGA-256 using Acrylate Cu AuNi ball origins from the leadframe. The size of MPP balls can be decreased, whereby the reliability of the BGA/CSP package is increased. This means that the higher eco-efficiency (= reliability indicator/environmental impact indicator) of MPP balls is plausible.

Per same size ball, the life cycle calculation showed that the metal mass can be reduced by 67–88%, but this study indicates that the correlation to environmental effects is low.

It is difficult to judge how much of the BGA/CSP will be recycled, and the issue is out of reach for IC Tier 2 manufacturers.

Weighting methods such as the Eco-Indicator'99 are based upon many assumptions. Recently, US scientists estimated a new ozone depletion potential, 0.017 kg CFC-11 equivalents/kg, for dinitrogen monoxide ( $N_2O$ ; Ravishankara et al. 2009). Their estimation would roughly translate to  $1.4 \times 10^{-5}$  DALY/kg. However, the ozone depletion is weighted too low in the Eco-Indicator'99 (H) for the  $N_2O$  to have significant effect on this research. Anyway, for ozone layer categories, from now on,  $N_2O$  will dominate many LCA studies.

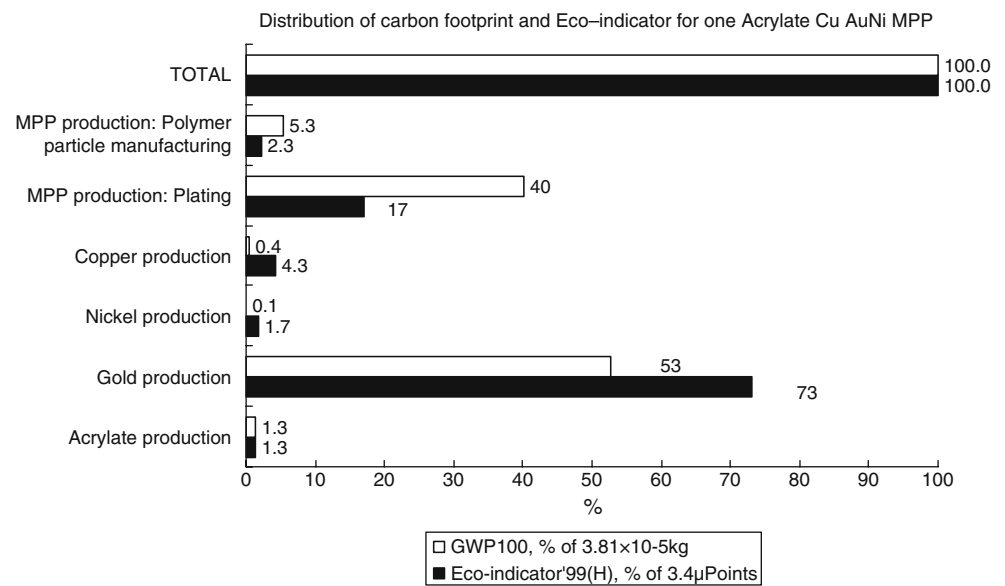


**Fig. 9** The environmental effect per BGA-256 life cycle of changing metal balls to metal-plated MPP

## 5 Conclusions

The ball share of the BGA-256 GWP100 and Eco-Indicator'99 (H) score is small, and the BGA/CSP producers can marginally improve the environmental performance by focusing on the balls. On a comparable IC packaging basis, the introduction of WCSP packaging technology implies a significant environmental footprint reduction. On PCBA level, the contribution from BGA balls is negligible. Results for MPP BGA balls suggest that gold usage is the key environmental performance indicator

**Fig. 10** The distribution of carbon footprint and Eco-Indicator'99(H) for one Acrylate Cu AuNi MPP

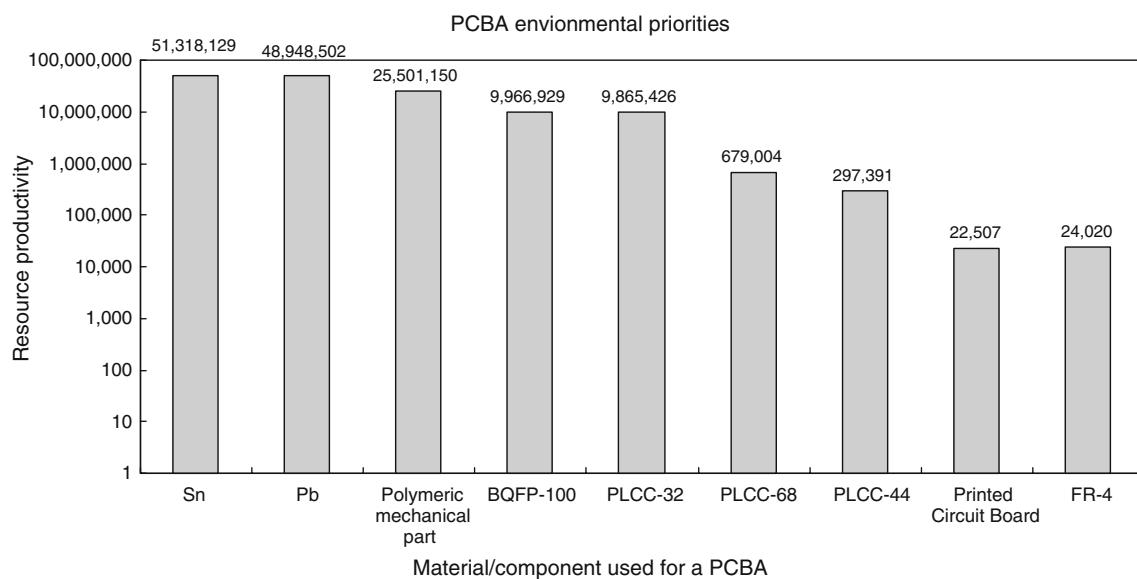


of interest. The eco-efficiency of using gold makes up for it to a certain degree. Especially, MPP balls of reduced size and identical functionality plausibly demonstrate eco-efficiency by being more reliable. For MPP balls, the eco-efficiency scores increase with decreasing ball diameter.

## 6 Recommendations and perspectives

Screening process-sum LCA is good enough for a Tier 1 and Tier 2 IC supplier companies to find the best ways to improve environmentally their technologies. Even though WCSP clearly reduces the component level impacts, the PCBA (board) level impact could increase as the CSP miniaturisation

is paralleled with *more* PWB layers. This effect should be included in further system expansions. Moreover, LCA and environmental impact evaluation is a relatively young research field, and each year, several new models and relatively bold hypotheses are presented. Two examples follow here. First, Eckelman (2011) recently presented nickel production data showing that the production energy varies by a factor of 200 on a contained nickel basis. This suggests large uncertainties in the use of global average life cycle inventory data for metal production and calls for geographical specific LCI data. Second, all LCIA methods (which include ozone depletion) need an update with the latest scientific data (Ravishankara et al. 2009). It is beyond this paper to explore the implications of these important findings.



**Fig. 11** The resource productivity of different materials and components used on a PCBA

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